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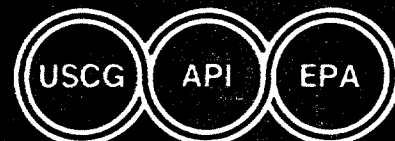
REMOTE THICKNESS MEASUREMENT OF OIL SLICKS ON WATER BY LASER-ULTRASONICS

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ABSTRACT: *At the National Research Council of Canada Industrial Materials Institute, research is in progress on the application of laser-ultrasonics to remote measurement of the thickness of oil on water. Laser-ultrasonics is a novel technique developed for the nondestructive inspection of materials. It uses a short pulse laser for the generation of ultrasonic waves in the oil layer and a second laser, coupled to an optical interferometer, for the remote detection of the ultrasonic surface motion. Direct measurement of the time of flight of the ultrasonic wave provides the value of the thickness of the oil layer. Application of this technique to thickness measurement of oil on water has been studied in small and large scale laboratory tests. Small scale tests demonstrate the direct and unambiguous determination of the oil layer thickness. Accuracy is essentially limited by the knowledge of the acoustic properties of the oil. Large scale tests show that a distance of almost 37 meters does not severely impede the method, so airborne application appears possible. Surface motion such as that caused by sea waves does not reduce the accuracy of the thickness determination but does limit the measurement rate. Preliminary airborne tests with a single laser probe confirm that laser-ultrasonics monitoring of the thickness of an oil spill is feasible.*

Remote sensing is an important tool in oil spill management. Cleanup personnel have recognized that remote sensing can increase the effectiveness of countermeasures. Remote sensing can also provide a better understanding of the physical behavior of an oil slick. Presently numerous systems are available commercially that can identify the presence and position of oil on water.[2] However, no absolute method is available for the remote measurement of the thickness of oil on water. Laser-ultrasonics, a novel technique developed for nondestructive evaluation of materials at the National Research Council of Canada Industrial Materials Institute (IMI), seems to be a promising avenue for such a remote measurement. This technique combines the precision and unambiguousness of thickness determination by ultrasonics with the remote sensing capability of optics.

The principle of thickness measurement by ultrasonics is rather simple. Let us assume that a high frequency ultrasonic pulse has been launched through a sample by a suitable transducer. When it reaches the back surface, or the interface in the case of liquids, it is partially transmitted and partially reflected back toward the surface. After a delay proportional to the thickness of the sample, this reflected acoustic pulse reaches the surface causing a displacement that can be monitored by the launching ultrasonic transducer. This echo of the initial pulse is reflected back toward the bottom of the sample. The ultrasonic pulse travels, therefore, back and forth partially losing its energy by attenuation in the sample itself and partially by transmission through the interfaces. It produces a periodic surface displacement. If the acoustic velocity in the sample is known, measurement of the time delay between the arrival at the surface of two consecutive echoes yields an accurate measurement of the sample thickness. This thickness measurement technique requires access to only one surface of the sample. It requires, however, that the acoustic impedance of the sample and of the backing medium are sufficiently different so that a sizable fraction of the acoustic energy is reflected back towards the surface.

Generally, the delay is determined by cross-correlation of two consecutive echoes. If the medium is not dispersive, that is, if the acoustic velocity is not a function of frequency, the error in the estimate of the delay is inversely proportional to the bandwidth of the acoustic pulse and to the signal-to-noise ratio.[3] This provides a high precision of the delay estimate, and hence, a high precision of the thickness measurement.

Conventional ultrasonics requires contact between the sample and the transducer, which is not always possible. For example, in steel mill applications, the temperature of the sample is sometimes too high to be sustained by the transducer. In these cases, a noncontact probing system is needed. Laser-ultrasonics, which uses a high power pulse laser to generate the ultrasonic pulse and a second probe laser to monitor the surface displacement resulting from the ultrasonic echoes, eliminates these difficulties.[5]

In laser-ultrasonics, the absorption of the high power laser pump pulse produces a thermal pulse in the sample. The thermal pulse generates a rapid thermal expansion of the sample near the surface where the laser beam was absorbed. The resulting pressure wave produces a steplike rise of the sample surface as well as an acoustic pulse of high frequency and large bandwidth, typically about 15 MHz in the case of oil. After a delay determined by the thickness and the acoustic velocity of the sample, the acoustic pulse returns to the surface
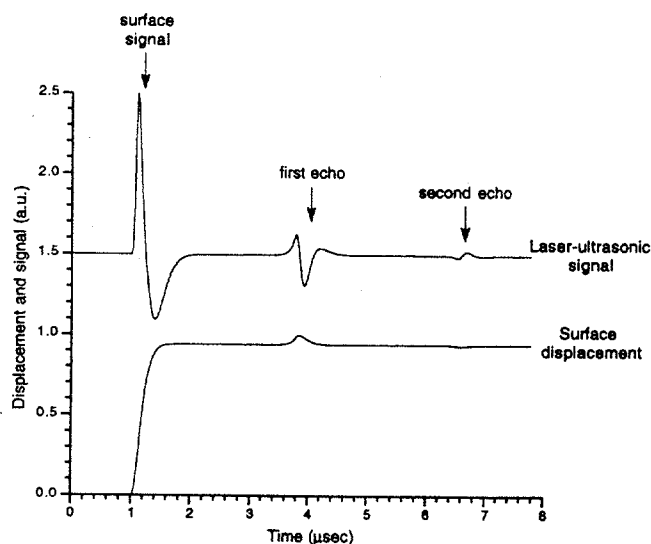
Figure 1. Theoretical displacement observed at the surface of an oil layer on top of water following laser excitation and corresponding laser-ultrasonic signal

and produces a slight surface displacement. Figure 1 shows the surface displacement, as function of time, of a 2 mm oil layer on water generated by a 100 mJ laser pulse with a 100 ns rise time. (Physical properties of oil and water used for this calculation are given in Table 1.) Notice the sharp initial step displacement, which is followed by the echoes.

To measure the surface displacement, a second laser beam, the probe beam, is directed onto the surface of the sample. The surface motion produces a phase shift or frequency shift (Doppler effect) upon the reflected probe beam. The ultrasonic surface displacement is therefore encoded as a frequency or phase modulation of the probe beam. To perform the demodulation, IMI has developed a technique based on a confocal Fabry-Pérot laser interferometer.[5] The Fabry-Pérot acts essentially as a very narrow optical filter which directly performs the light demodulation when the laser probe frequency has been set on one of the slopes of the filter response (approximately at half height). This technique is very insensitive to low frequency motions, such as those generated by vibrations, and highly sensitive to high frequency surface displacements generated by the ultrasonic pulse. Additional low frequency filtering is usually added to reduce the noise level further. Figure 1 also shows a typical signal provided by the Fabry-Pérot system after additional electronic filtering. This signal corresponds to the surface displacement previously calculated. As seen in this figure, the surface signal and the echoes have different shapes. This is caused by the different origins of each signal and the effect of the low frequency filtering. Notice how the high sensitivity of the detection system permits clear observation of the second echo, which is barely visible on the displacement curve.

In this article, we present experimental results in the application of laser-ultrasonics for the remote measurement of the thickness of oil on water. Since this technique can operate at a distance, it could be implemented, in principle, from an airborne platform. We present the results of small scale laboratory tests which demonstrate that laser-

Table 1. Acoustic and optical properties of oil and water

Property	Oil	Water
Acoustic impedance (Pa·s/m)	1.13×10^6	1.5×10^6
Acoustic velocity (m/s)	1410	1500
Density (kg/m³)	800	1000
Specific heat (J/kg·K)	250	1000
Thermal expansion coefficient (K^{-1})	1.0×10^{-4}	4.1×10^{-5}
Optical penetration depth at 10.6 μm (μm)	100	10
Optical reflectivity at 1.06 μm	4.5 %	2.0 %

ultrasonics directly provides the value of oil thickness on water. The results of a large scale demonstration are also given. Finally, we present the results of preliminary airborne tests that indicate that an acceptable measurement rate is feasible in real field situations.

Oil thickness measurement in laboratory

When a carbon dioxide (CO_2) laser is used, laser generation of ultrasound in oil is rather efficient. This is due to the strong absorption at the wavelength of this laser (10.6 μm) and to the rather high thermal expansion coefficient of oil, especially compared to most solids. Only a small amount of optical energy is needed to generate fairly large surface displacements. Theoretical calculations show that a peak surface displacement of 15 μm is obtained for a 1 J/cm² pump energy density for oil as compared to 15 nm for the same pump energy density in the case of steel. This high generation efficiency permits operation at large distances since the generation beam does not need to be tightly focused to obtain a sufficient energy density.

However, a particular difficulty arises in the case of oil on water from the weak acoustic impedance mismatch between oil and water, as indicated in Table 1, giving a weak acoustic reflection coefficient. For a clear observation of the echoes, a strong acoustic reflection at the interface would be preferable. A reflection coefficient of only 14 percent (17 db) is calculated using typical acoustic parameters of oil and water shown in Table 1. The amplitudes of the echoes therefore are markedly smaller due to impedance at the oil-water interface. It should be noted that the acoustic properties of oil and water vary as a function of environmental conditions. In particular, emulsification tends to make the acoustic properties of the oil layer even closer to those of water, and hence to reduce further the reflection coefficient.[4]

Since we expect a rather low amplitude of echoes, high sensitivity is required at detection. In any interferometric detection technique for ultrasound, and in particular with the confocal Fabry-Pérot interferometer scheme, sensitivity is essentially determined by the light intensity received by the detector.[5] Fortunately, oil is a very good specular reflector at 1.06 μm, the probe beam wavelength used. The probed surface is fairly flat, with the exception of the ripples of capillary waves when air is blowing above it. This has the consequence that the reflected probe beam has a low divergence and that most of its intensity can be collected with a relatively simple optical telescope of sufficient aperture. The main loss affecting the probe beam intensity is caused by the low optical reflection coefficient of oil, about 4.5 percent at the probe beam wavelength. This loss is not a severe problem since the probe laser has a very high intensity.

The accuracy of the oil thickness measurement by laser-ultrasonics is determined by both the precision of the determination of the time delay between echoes and by the accuracy of the value of the acoustic velocity of oil. In this case, it turns out that the larger error lies with the value of the acoustic velocity of oil. Published data show that the acoustic velocity of crude oil varies as a function of the concentration of its different constituents and with temperature.[6] In a remote sensing application, it will not be possible to determine either oil concentration or temperature. However, several experiments performed at IMI show that the temperature variation of the acoustic velocity is weak, less than 3 percent for a temperature variation from 5° C to 15° C. The impact of the composition of oil is more difficult to assess. Published data show that the velocity variation can be as high as 25 percent.[6]

We have performed several experiments in the laboratory to evaluate the use of laser-ultrasonics for remote measurement of the thickness of oil on water. A typical experiment is described below. A 5 mm thick layer of Norman Wells North-West Territories crude oil was spread on tap water in an 8 cm diameter beaker. The oil was weathered for at least 16 hours before the measurement. A 4 cm depth of water was used to prevent any interference echo from reflection by the bottom of the beaker. The temperature of the oil-water bath was about 22° C.

The CO_2 generation laser used was a Laser Science (10.6 μm wavelength) TEA pulse laser with a pulse width of approximately 100 ns and a pulse energy of 200 mJ. The beam was spatially filtered to provide a single mode Gaussian distribution at the surface of the sample. The beam diameter on the sample was 4 mm giving a 399 mJ/cm² energy density at the oil layer surface. The probe beam was a long pulse YAG laser (1.06 μm wavelength, approximately 50 μs pulse width) previ-
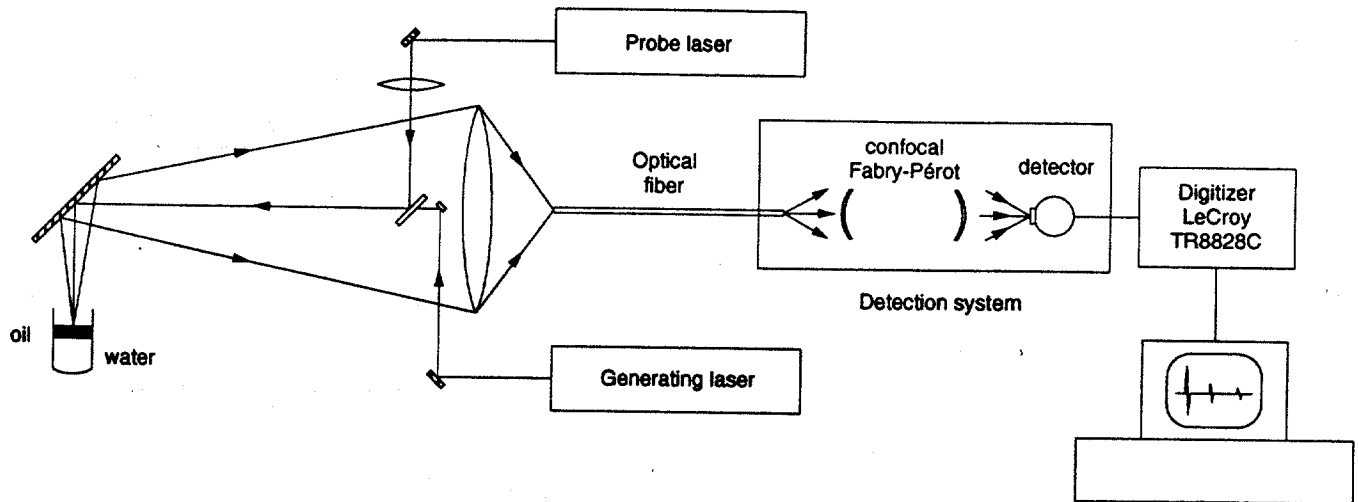
Figure 2. Diagram of the laser-ultrasonic system for the remote sensing of oil on water

ously developed by IMI and Ultra-Optec Inc. for laser-ultrasonic material inspection. This laser is frequency stabilized to the Fabry-Pérot interferometer to perform frequency demodulation properly. Peak amplitude of the probe laser beam was adjusted to obtain near saturation of the detector, that is, maximum sensitivity of the system. The probe beam was focused by a single lens onto the sample to a spot size approximately equal to that of the CO_2 laser. No optics were used to focus the CO_2 pump beam. A Ge beam mixer was used to superimpose colinearly the probe and pump beams. Both beams were directed to the center of the beaker to prevent any interfering effect by surface waves reflected by the beaker walls. The reflected probe beam was collected by a 5 inch diameter lens and focused onto an optical fiber, which transmits the reflected probe beam light to the confocal Fabry-Pérot. The sample was located about 2 meters from the 5 inch diameter lens of the optical system.

Data acquisition was performed with a LeCroy TR8828C digitizer at a sampling rate of 25 MHz. The signal was filtered to eliminate low frequency noise. Data acquisition was controlled with a personal computer using UDASP, a software program developed by IMI and Ultra-Optec Inc. Each signal was 1024 sampling points long, that is, recorded over a 40.96 μs time window. Thirty consecutive data acquisitions were averaged to eliminate spurious fluctuations of the intensity of the probe beam, which affect the signal. A diagram of the complete experimental setup is shown in Figure 2.

Figure 3 shows the laser-ultrasonic signal recorded for this oil-water sample. We can clearly observe the surface signal and the echoes. Notice that the surface signal just barely saturates the detector. Also notice that the surface signal has a shape quite different from the echoes, as expected. The inversion of the second echo with respect to the first echo follows from the higher acoustic impedance of water compared to oil, which gives a noninverting reflection (there is inversion at the oil-air interface). The amplitude of the echoes shows a rapid drop, to about 12 percent (18 db). This is in reasonable agreement with the expected 14 percent (17 db) estimated previously. The attenuation of the acoustic pulse in the oil layer is mainly due to the transmission loss into water. The shapes of the echoes are consistent with each other; therefore, a direct cross-correlation estimate of the delay is possible. A low frequency oscillation seen at times greater than 30 μs is caused by intensity fluctuations of the probe beam, which are not completely eliminated by averaging.

Direct measurement of the oil thickness gives a value of 5 mm ± 2.5 mm. The large error in determining the thickness accurately is due to the capillary properties of oil. The laser-ultrasonics thickness measurement of the oil sample is calculated by using an acoustic velocity of 1410 m/s with an error of 1 percent, as determined experimentally at IMI for this type of oil using conventional ultrasonics. With the cross-correlation between the two consecutive echoes of Figure 3 and the known acoustic velocity, we deduce an oil thickness of 6.23 mm with an accuracy of 1 percent, limited by the accuracy of the acoustic velocity.

As can be seen in Figure 3, the amplitude of the second echo is relatively weak. In most cases, especially in actual remote sensing, the signal-to-noise ratio will not be sufficient for the observation of this second echo. Cross-correlation delay estimates can only be performed by using the surface signal and the first echo. However, the shapes of these two signals are not identical. This will introduce an error in the estimation of the thickness. The cross-correlation estimate of thickness obtained by using the surface signal and the first echo is 6.26 mm. This is only different by 0.5 percent from the value deduced by the cross-correlation of the consecutive echoes. Theoretical simulations show that this error is a function of the Fabry-Pérot configuration and of the pump beam pulse energy (which produces nonlinear effects at detection). Generally it is less than 1 percent,[1] and is therefore much smaller than the error resulting from the uncertainty associated with the acoustic velocity.

Our small scale experiments have demonstrated that laser-ultrasonics can be used for the noncontact thickness measurement of oil on water. Due to the relative acoustic properties of oil, weathered oil, and water, the estimate of the oil thickness will be performed by cross-
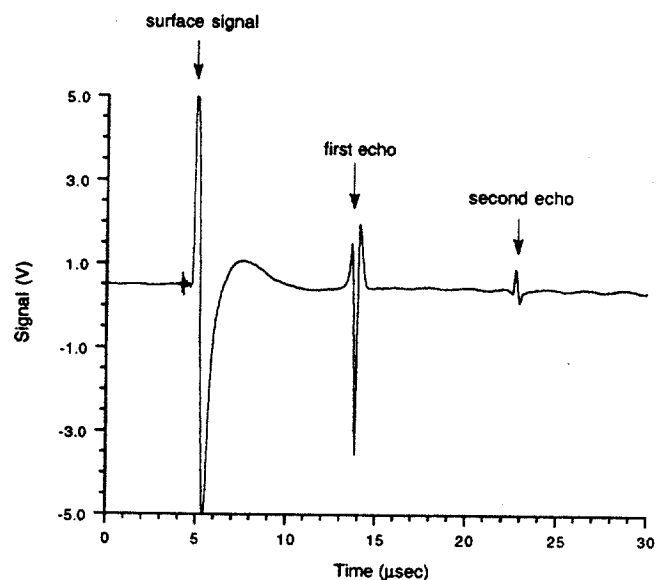

Figure 3. Laser-ultrasonic signal, average of 30 data curves, of an oil layer on water—direct thickness observation; 5 mm (± 50%), laser-ultrasonic estimate: 6.23 mm (± 1%)

correlation of the surface signal with the first echo. The accuracy of the measurement is limited by the accuracy of the value of the acoustic velocity of the oil. The next step to assess the feasibility of using the technique in remote sensing conditions is to increase the probing distance much farther.

Large scale test

The main problem of any remote sensing technique is one of sensitivity. In the case of laser-ultrasonics remote sensing, the sensitivity depends upon the generation efficiency and the minimum displacement that can be detected. Generation efficiency is primarily determined by the concentration of pump beam energy that can be achieved at a large distance. The minimum detectable displacement is determined by the amount of light that can be collected by the optical system at that distance. A test facility was set up in the large scale laboratory of IMI to access the feasibility of remote sensing measurement of oil thickness on water.

A pool, 3 meters in diameter and 60 cm deep, was used to hold the oil-water sample. Oil layers from 250 μm up to 35 mm were studied. Two mirrors suspended from the ceiling and two lying on the floor were used to fold the laser beams' path to obtain an equivalent laser system-to-sample height of approximately 37 meters. The folding mirrors were cheap off-the-shelf, aluminum-coated glass and had appreciable losses. The total round-trip transmission of the four mirrors at the probe wavelength was measured to be only 15 percent. This attenuation results in a loss of probe beam intensity and, hence, in a significant reduction of the signal-to-noise ratio.

We used the same system for generation and detection as the one used for the small scale investigations, with the exception of the focusing and collecting optics. The probe and pump beams were focused to a spot size of about 1 cm diameter by using two-lens beam expanders. The same exit lens was used by the two beam expanders so the system had a single optical axis at its exit. The collection optics of the probe beam was a 40 cm diameter mirror telescope that focused the received light into an optical fiber used for transmission to the confocal Fabry-Pérot interferometer. The collection optics had a total angle of acceptance of 11 mrad.

Initially, experiments were performed with the same surface conditions as for our small scale test, that is, an oil layer on a static flat surface of water. The probe beam intensity was adjusted as before to give maximum signal-to-noise ratio. Figure 4 shows the laser-ultrasonic signal recorded for a 5 mm thick layer of Norman Wells Northwest Territories crude oil on water. We noted that the signal-to-noise
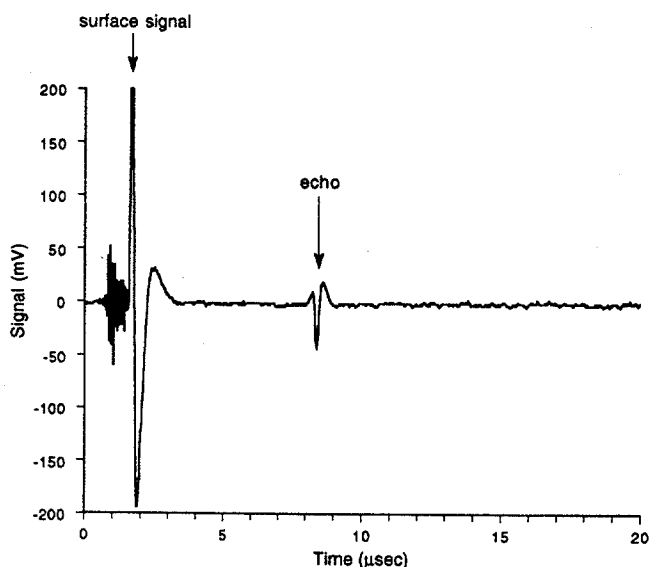
ratio was lower than that of Figure 3 obtained during the laboratory tests and allowed us to observe only the first echo. This reduction resulted from losses caused by the folding mirrors. Note also that the data of Figure 4 corresponds to a single shot and has not been averaged as in Figure 3.

These initial experiments have therefore shown that, under static conditions, our laser-ultrasonic system can measure the thickness of oil on water at a distance of 37 meters. But in the field, the surface is never really flat or static, due to the presence of sea waves and wind-generated surface ripples. The scale of the surface disturbance being, in first approximation, at least larger than the laser spots on the surface, the effect of the surface perturbation can be represented as a continuously oscillating or tilting mirror (with two degrees of freedom). If the surface tilt is larger than a quarter of the acceptance angle 2.75 mrad of the optical collection system, then the beam is not reflected back into the detection system, thus preventing any thickness measurement. For proper and efficient operation of a field system, it is therefore necessary to monitor the surface tilt and to fire the pump and probe lasers only when the sample surface is at an acceptable tilt angle. This feature, necessary, for a field system, was implemented and tested during these large scale tests. For this purpose, a third laser, a 10 mW continuous HeNe laser, was used. This beam was launched along the same optical axis as the probe and pump beam onto the surface. Reflected light from this laser was monitored by an additional detector and used to generate a trigger signal for firing the pump and probe lasers.

To assess the impact of surface waves on the remote sensing of oil thickness, surface ripples were generated by blowing air with a fan. The triggering scheme was used during these tests, leading to laser firing and data acquisition only when the surface had the proper tilt. Figure 5 shows a typical signal recorded in these conditions which shows clearly the surface feature and the echo, allowing adequate thickness measurement. The signal-to-noise ratio observed in the case of the rippled surface is generally less than in the static case (compare Figure 5 and Figure 4). This is explained by the fact that the surface is no longer a perfectly flat optical reflector but is given a slight curvature by the presence of waves. The reflected probe beam is, therefore, more diverging and, hence, less light is actually received by the collecting optics. This in turn results in a lower signal-to-noise ratio. This effect is more severe with capillary waves of short wavelength which lead to higher surface slopes. Fortunately these waves are highly damped by oil, especially crude oil.

During these tests, two levels of wave generation were used. As we increased the intensity of the ripples, the acquisition rate was found to
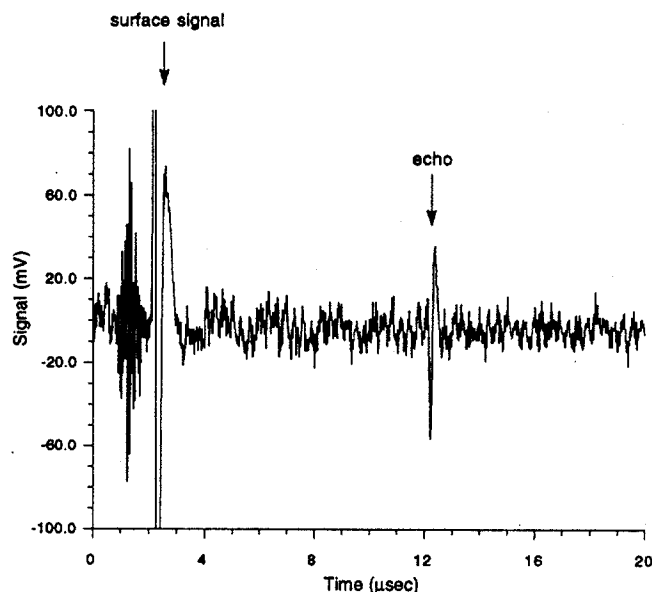
Figure 4. Laser-ultrasonic signal, single shot, of a 5 mm thick oil layer on water; 37 meters between the sample and the laser system

Figure 5. Laser-ultrasonic signal observed from a 7.2 mm thick oil layer on agitated water surface; 37 meters between the sample and the laser system

decrease rapidly. From a rate of 1 acquisition per second for light ripples, the rate fell to a level of 1 acquisition per 3 seconds for strong ripples. Note that no precise measurements of the amplitude of the ripples were made. Extrapolation to actual sea conditions is difficult on the sole basis of these data. It should be noted that, in actual remote sensing from an airplane, the pitch and roll of the airplane would have the same effect as the surface tilt induced by waves. It is also suspected that the high velocity of the plane would provide rapid scanning in one direction over a large area and consequently increase data acquisition rate (see below).

The large scale test demonstrates that remote sensing of oil thickness on water is possible by laser-ultrasonics. As we have seen during the small scale experiments, these tests also show that laser-ultrasonics provides a direct and unequivocal measurement that can be used to determine the oil layer thickness. The signal-to-noise ratio was found reduced compared to the small scale tests, essentially because of the large distance and of the effect induced by waves, but was sufficient to yield adequate thickness information. However, the reduced rate of acquisition caused by waves appears as a concern which was addressed by the airborne tests.

Preliminary airborne test

To establish clearly the effect of sea motion on the measurement rate, a preliminary airborne test was performed using only the trigger laser and monitoring the collected light from the sea surface. The system was mounted on a DC-3 aircraft of Innotech Aviation Inc. Remote Sensing Division. The system included only the trigger laser which was, as before, a 10 mW continuous HeNe laser. The beam was focused with the same two-lens beam expander as before to 91 meters (300 feet) and to a spot approximately 1.5 cm in diameter. The receiving optical system was a 40 cm mirror telescope, previously used in our large scale tests, adjusted to a distance of 91 meters. This configuration corresponds to a full angle of acceptance of 4 mrad. Light collected by the mirror telescope was focused into an optical fiber identical to the one used to couple light to the confocal Fabry-Pérot in the complete laser-ultrasonic system. The amount of light at the output of the fiber was measured by a photo diode. Data acquisition was performed with a Signatec DASP100 card housed in a 386 personal computer, controlled by a software program specially developed for this particular application. Each data sample was 2048 points long and the sampling rate was 1.56 MHz. The maximum acquisition rate was 3 Hz, limited by the acquisition program. The tests were conducted from November 29, to December 1, 1991, near Halifax, Nova Scotia, about 20 to 30 miles off the coast, near Beaver Island. The tests were performed at a minimum height of 91 meters (300 feet) to a maximum height of 210 meters (700 feet). Data collection rates were measured for different heights, plane velocities, and angles of flight path with respect to the sea wave propagation (essentially the wind direction).

During these tests, the intensity of the reflected beam was continuously monitored by the system. When the intensity at the detector was above a given threshold, the data was automatically recorded by the computer and stored on disk with the time of acquisition. During these tests, no oil was present on the sea surface. The optical reflection coefficient of sea water (2 percent) being lower than that of oil (4.5 percent) at the laser beam wavelength, one should expect better results in the case of an actual spill.

Figure 6 shows a typical signal recorded by the system. The two sharp spikes are generated by the electronic trigger of the acquisition system. The first spike was triggered when the light intensity at the detector reached the threshold level, which was set at 120 mV after signal amplification. This level corresponded to an intensity of 13 nW. This first pulse was used to command data storage on disk. The second electronic pulse was triggered after a fixed delay of 350 μsec and was used to reset the permanent data sampling. This mode of operation permitted us not only to count nearly all the useful light pulses but also to record their shapes. The 3 Hz limit mentioned above resulted in missing a few closely spaced pulses in some cases but this had no significant impact on the overall conclusion that can be drawn from this experiment.

These tests show that the rates of acquisition in actual remote sensing conditions are much higher than those observed during our large scale laboratory tests, even though the acceptance angle was half
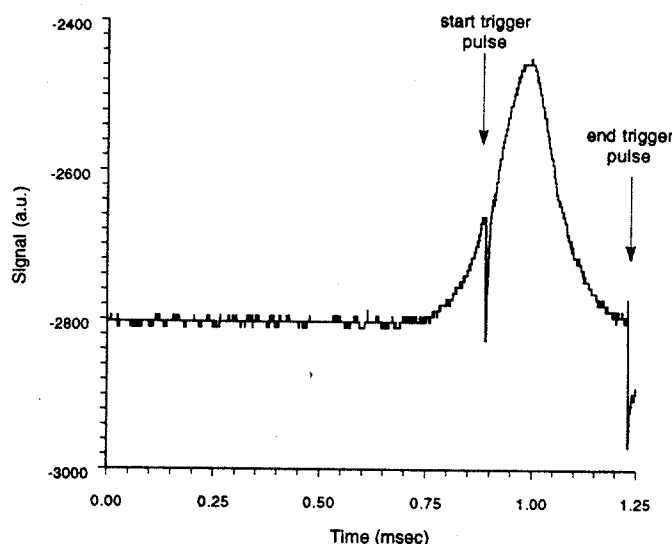

Figure 6. Typical light collection signal observed during the airborne tests

that of the large scale tests. This confirms our previous suggestion that the motion of the plane increases the probability of finding a probed area over the sea surface with a suitable orientation.

Our results also show that the rate of acquisition is strongly dependent upon airplane height above sea level. We observed an average rate of 1 Hz at 91 meters down to 0.2 Hz at 150 meters. Trials were made at 210 meters but no triggering was observed, probably because of improper adjustment of the optical system for this height. As plane altitude increases, the acceptance limit angle of the probed area becomes smaller, and hence the probability of finding such an area is reduced. Notice that these are only average values. Data show that delays between consecutive triggers as short as 0.3 s (the minimum delay given the acquisition program) and as long 10 s can be observed for both altitudes, although longer delays are more frequent at 150 meters.

In conclusion, these airborne tests demonstrate an adequate rate of data acquisition in real field conditions. We suggest that this rate can be increased by a scanning-type light collecting system that would actively search for optimum conditions.

Conclusions

We have demonstrated that laser-ultrasonics is a promising technique for measuring the thickness of an oil slick by remote sensing. As demonstrated by small scale laboratory experiments as well as large scale tests, laser-ultrasonics provides a direct way to determine the thickness. If the ultrasonic echo from the oil-water interface is observed, then the thickness can be calculated. The accuracy of the determination is essentially limited by the uncertainty associated with the value of the acoustic velocity of the oil in the spill. Large scale laboratory tests have demonstrated that the technique can be applied at considerable distance and have shown that the data acquisition rate is limited by the surface motion. Preliminary airborne tests have shown that, in actual field conditions, this rate is sufficient for adequate thickness mapping of an oil slick. Field tests with a complete laser-ultrasonic system are to be conducted in the fall of 1992.

Acknowledgments

References

1. Choquet, Marc and Jean-Pierre, Monchalin, 1990. Modeling of thermoelastic generation of ultrasound in oil upon water. Internal Industrial Materials Institute Report
2. Fingas, Merv, 1990. The technology of oil spill remote sensing, *Spill Technology Newsletter*, v15, n3, pp1–17
3. Knapp, C. H. and G. C. Carter, 1976. The generalized correlation method of estimation of time delay. *IEEE Transaction on Acoustic, Speech and Signal Processing*, v ASSP-24, n4, pp320–327
4. McClements, D. J. and M. J. W. Povey, 1989. Scattering of ultrasound by emulsions. *Journal of Physics D: Applied Physics*, v22, pp38–47
5. Monchalin, Jean-Pierre, 1986. Optical detection of ultrasound. *IEEE Transaction on Ultrasonics, Ferroelectric and Frequency Control*, vUFFC-33, n5, pp485–499
6. Wang, Zhijing and Amos Nur, 1991. Ultrasonic velocity in pure hydrocarbons and mixture. *Journal of the Acoustical Society of America*, v89, n6, pp2725–2730